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April 1999

US Army Corps
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Waterways Experiment
Station

Hawser Load Test of Tow Moored to Downstream Guide Wall, Kentucky Lock, Kentucky

by Jose E. Sanchez, Guillermo A. Riveros

Prepared for U.S. Army Engineer District, Nashville

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3909 Halls Ferry Road
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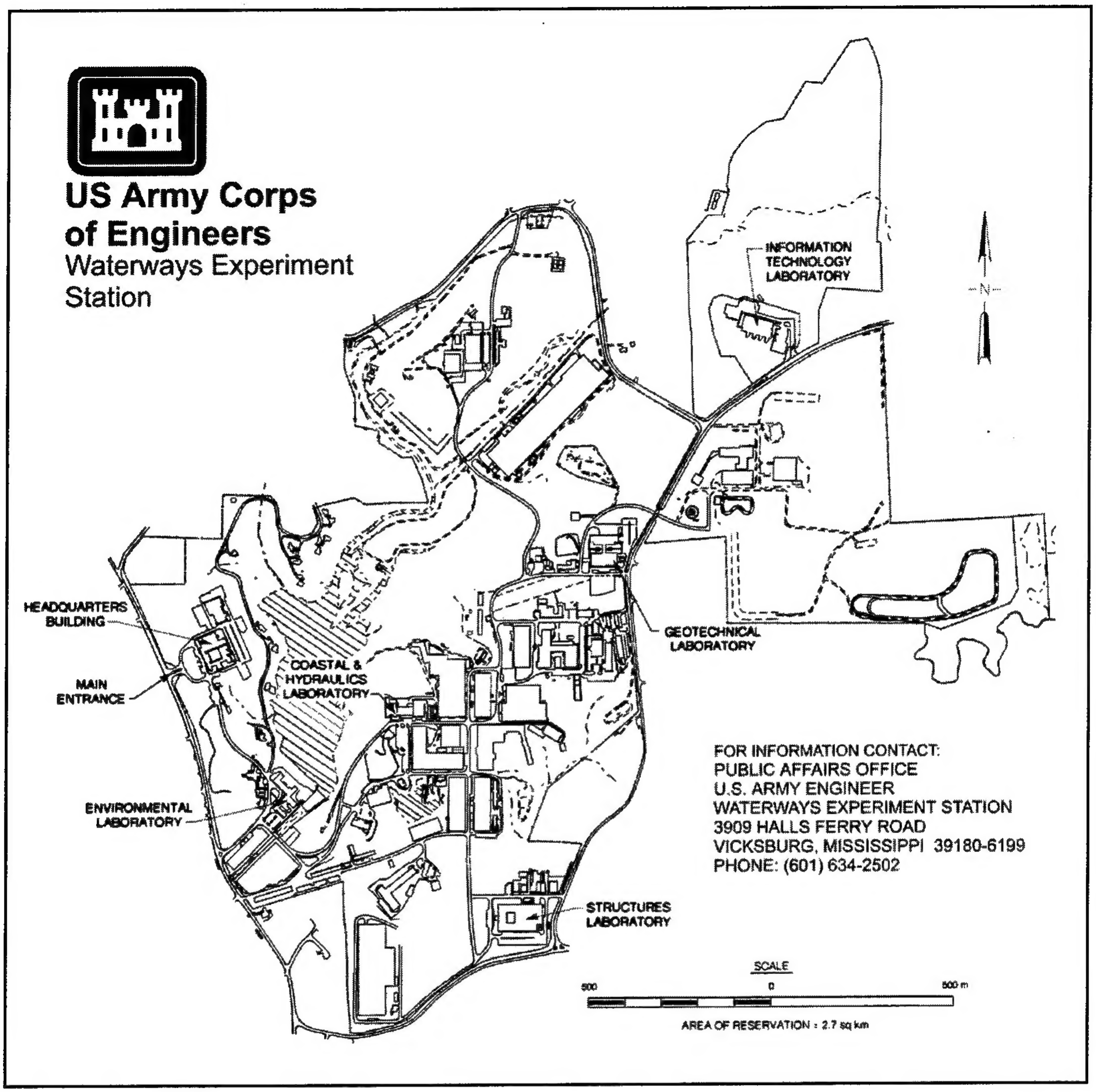
Final report

Prepared for U.S. Army Engineer District, Nashville
Nashville, TN 37202-1070



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Preface

The study reported herein was performed for the U.S. Army Engineer District, Nashville, and was authorized by the U.S. Army Engineer Division, Great Lakes and Ohio River, on 30 July 1997. Mr. Donald Getty, Nashville District, directed this study.

Work for the study was conducted in the Coastal and Hydraulics Laboratory (CHL) and the Information Technology Laboratory (ITL) of the U.S. Army Engineer Waterways Experiment Station (WES) during the period of September and October 1997 under the direction of Dr. James R. Houston, Director, CHL; Mr. Charles C. Calhoun (retired), Assistant Director, CHL; Dr. Phil G. Combs, Chief, Rivers and Structures Division, CHL; Dr. N. Radhakrishnan, Director, ITL; Mr. Tim Ables, Assistant Director, ITL; and Mr. H. Wayne Jones, Acting Chief, Computer-Aided Engineering Division, ITL. Experiments were conducted by Messrs. Jose E. Sanchez and Guillermo A. Riveros of CHL and ITL, respectively. The report was written by Messrs. Sanchez and Riveros.

At the time of publication of this report, Acting Director of WES was COL Robin R. Cababa, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers

1 Introduction

Purpose of Hawser Load Experiments

Hawser load information for tows moored to the downstream guide wall was needed by the U.S. Army Engineer District, Nashville, to aid in the design of the discharge outlet and guard wall for the 1,200-ft[1]-long lock addition proposed at the Kentucky Lock and Dam. The hawser load is simply the pull or tension in the mooring lines when a tow is tied to the wall. Review of the existing literature revealed that no data concerning this type of information were available. To obtain the necessary information, experiments were performed to determine the hawser loads experienced by tows moored to the lower guide wall of the existing 600-ft-long navigation lock and to develop an allowable hawser load.

General Description

The existing Kentucky Lock is located on the Tennessee River approximately 20 miles southeast of Paducah, KY (Figure 1). The project consists of a gated spillway to regulate river flows, a powerhouse for hydroelectric power generation, and a 600-ft-long navigation lock for moving industrial tow traffic and recreational boats through the project. Products from 20 States pass through the system of Kentucky and Barkley locks, the lowermost locks on the Tennessee and Cumberland rivers, respectively. Traffic levels are expected to increase in the future, and an additional 1,200-ft-long by 110-ft-wide lock is projected to be necessary to satisfy future capacity requirements.

Scope

Three experiments were conducted to determine the axial loads (tensile forces) in the mooring lines of towboats moored in the lower lock approach. These axial loads are the hawser forces in the mooring lines. The loads were computed from strain readings measured using the Structural Testing System

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vi.

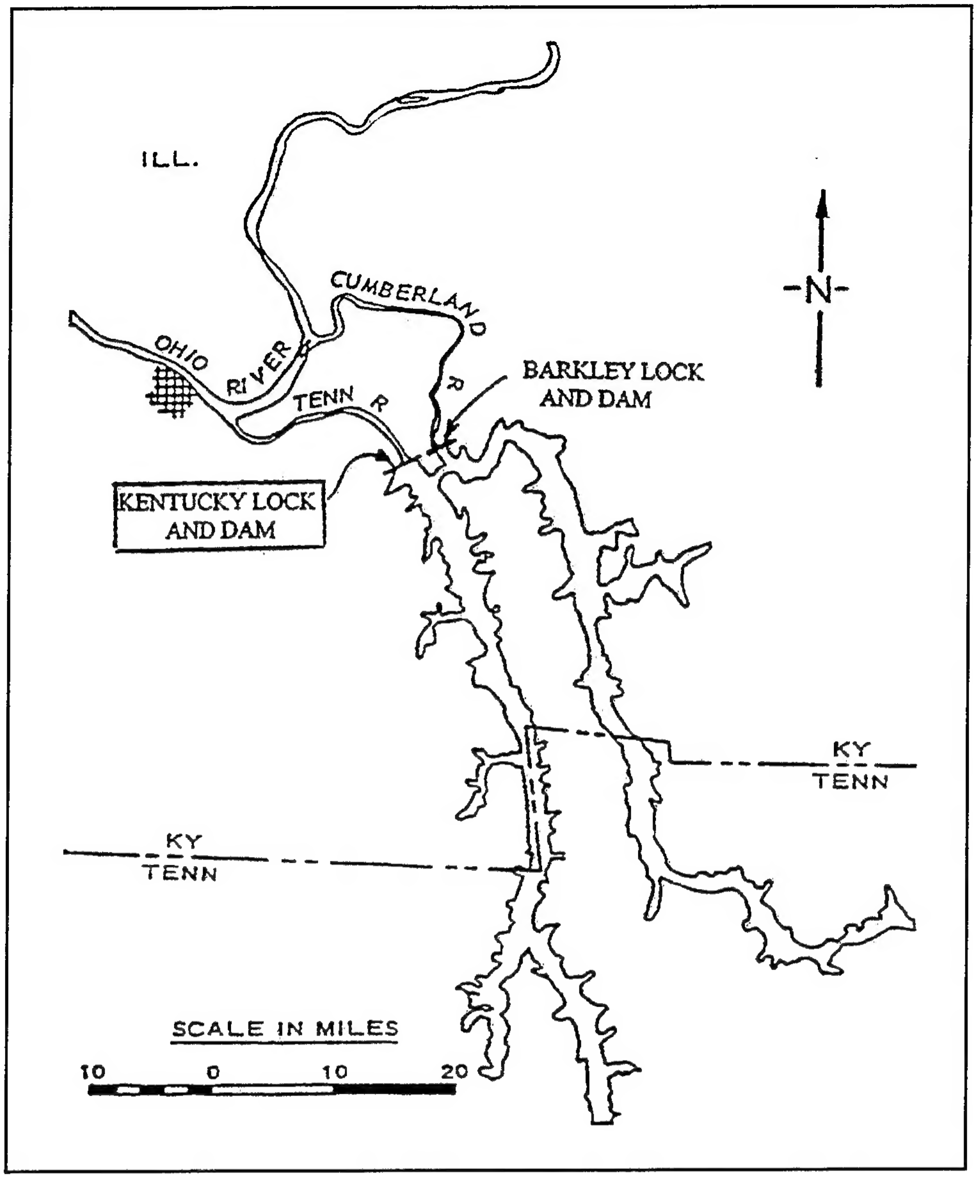


Figure 1. Vicinity map

(developed by Bridge Diagnostics, Inc., 1993). The first two experiments were conducted with the towboat anchored to the third mooring line, and the last experiment was performed with the towboat tied to the first mooring line (Figure 6). The lock operator used a step-valve procedure during the emptying cycle. In this procedure, the operator opened the emptying valves a certain distance at different time intervals until the valve was fully open. The first, second, and third experiments had emptying times of 23.5, 16.0, and 16.0 min, respectively. A structural steel coupling device (Figures 2 and 3) was used to connect the strain transducers to measure the forces. This report presents an explanation of the Structural Testing System used in these experiments and the experimental results.

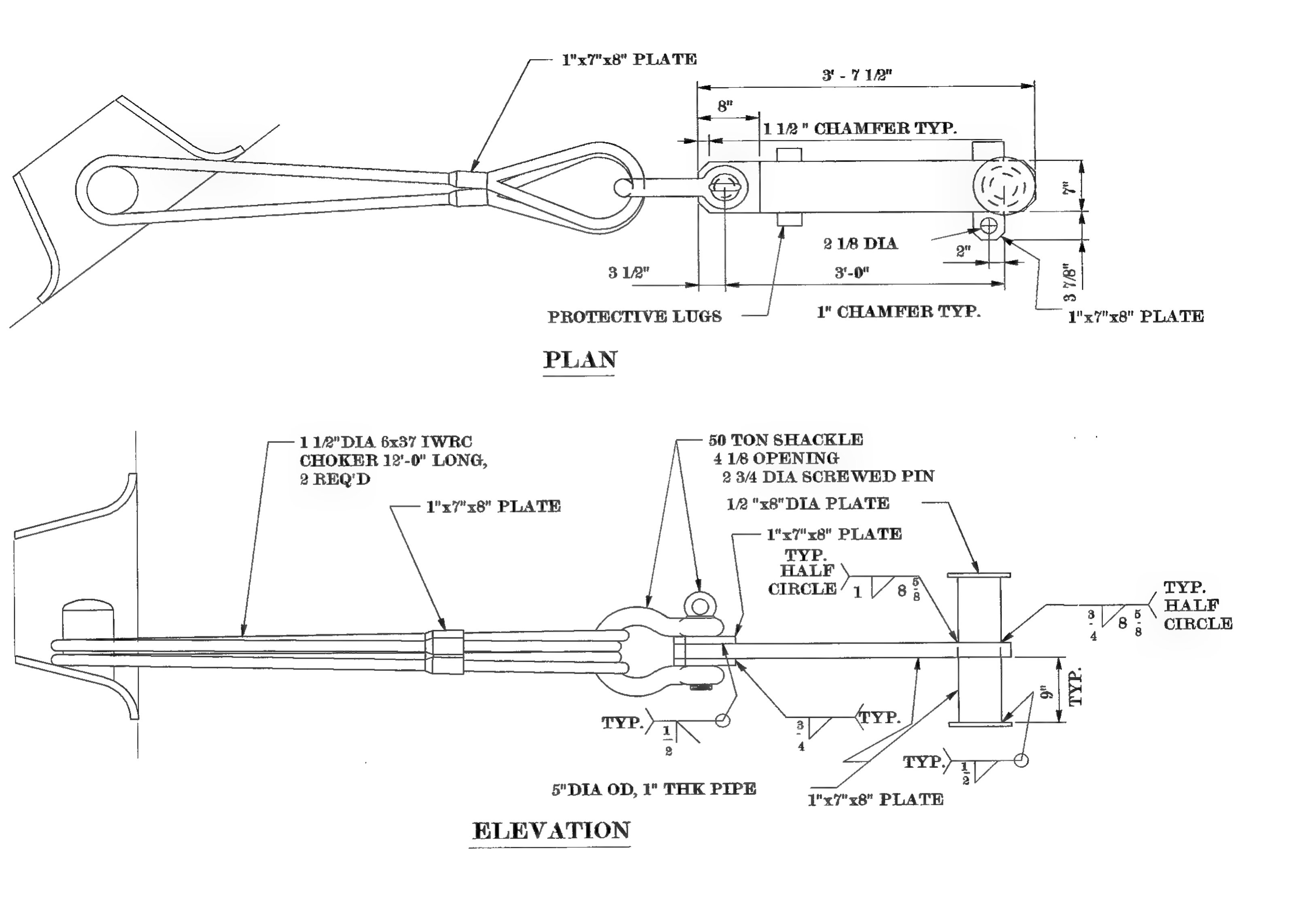


Figure 2. Plan and elevation view of coupling device

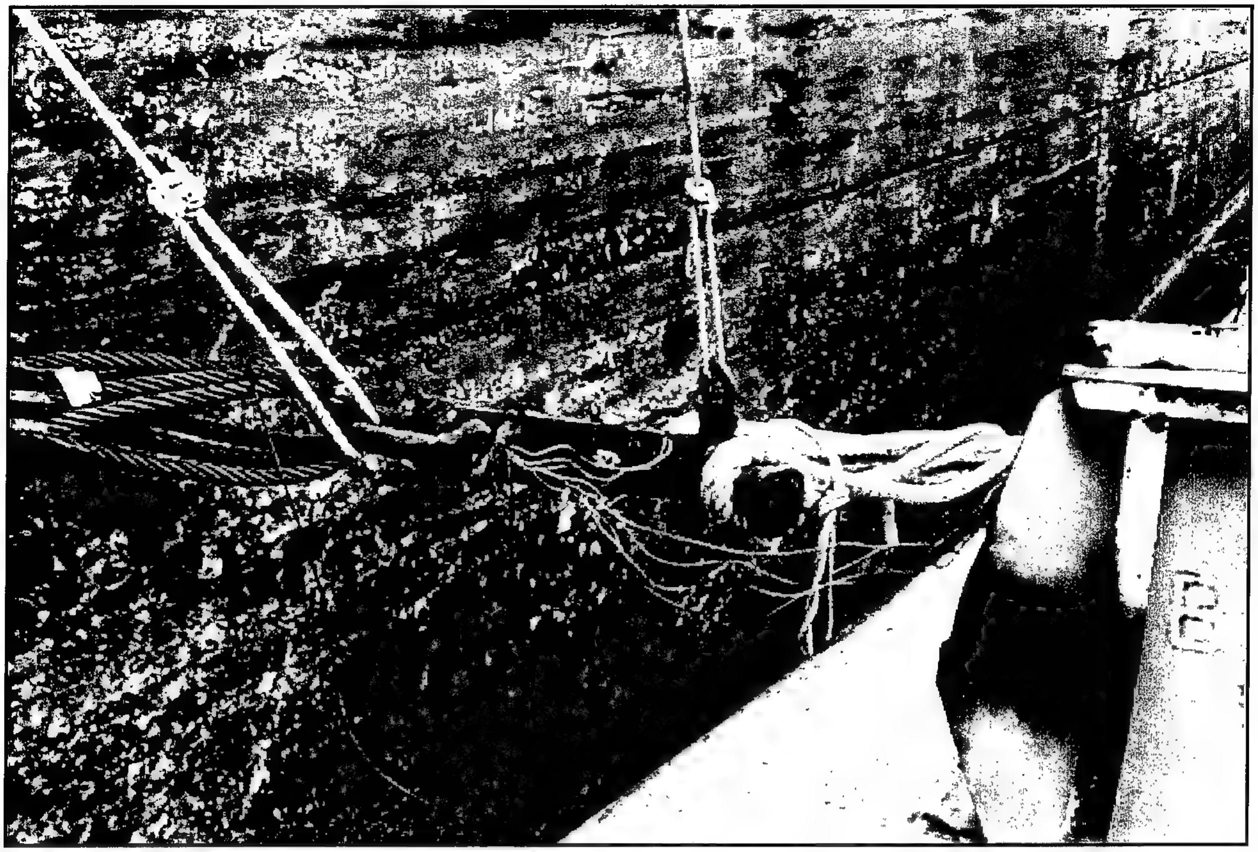


Figure 3. Coupling device system connected to wall and barge

2 Coupling Device and Location of Strain Transducers

Coupling Device

A coupling device was used to connect the barge to the guide wall. The device consisted of a structural steel plate 43.5 in. long, 7.0 in. wide, and 2.0 in. thick, connected to the mooring bit using steel cables and to the barge using ropes (Figure 2 and 3). On the guide wall side of the plate, a shackle was placed to connect the wire ropes to the wall (Figure 2 and 3). At this location, a cover plate 8.0 in. long, 7.0 in. wide, and 1.0 in. thick was installed on both faces of the main plate to provide additional stiffness to the device. At the other end (barge side), a 5-in. nominal diameter extra strong pipe was fillet welded to each side of the plate to connect the ropes to the barge.

Description and Location of Strain Transducers

The strain transducers used in the experiments were attached to the structural steel plate as illustrated in Figures 4 and 5.

The Structural Testing System originated from Bridge Diagnostics, Inc., of Boulder, CO, and is a complete strain measurement system including strain transducers, digital data acquisition electronics, and interface to a personal computer. Each transducer contains four electric resistance strain gauges in a full Wheatstone bridge circuit to form a uniaxial strain transducer and is mounted in a protective housing. The transducers have a gauge length of 3 in. and can be mechanically attached or attached with adhesive to structural members. The transducers are calibrated, and gauge factors and identifiers for each transducer are recorded in the system software providing automated direct strain readings.

Transducers were placed at the center line of the weak and strong axis planes. This location will provide the strain diagrams for both planes that will be used to calculate the axial load.

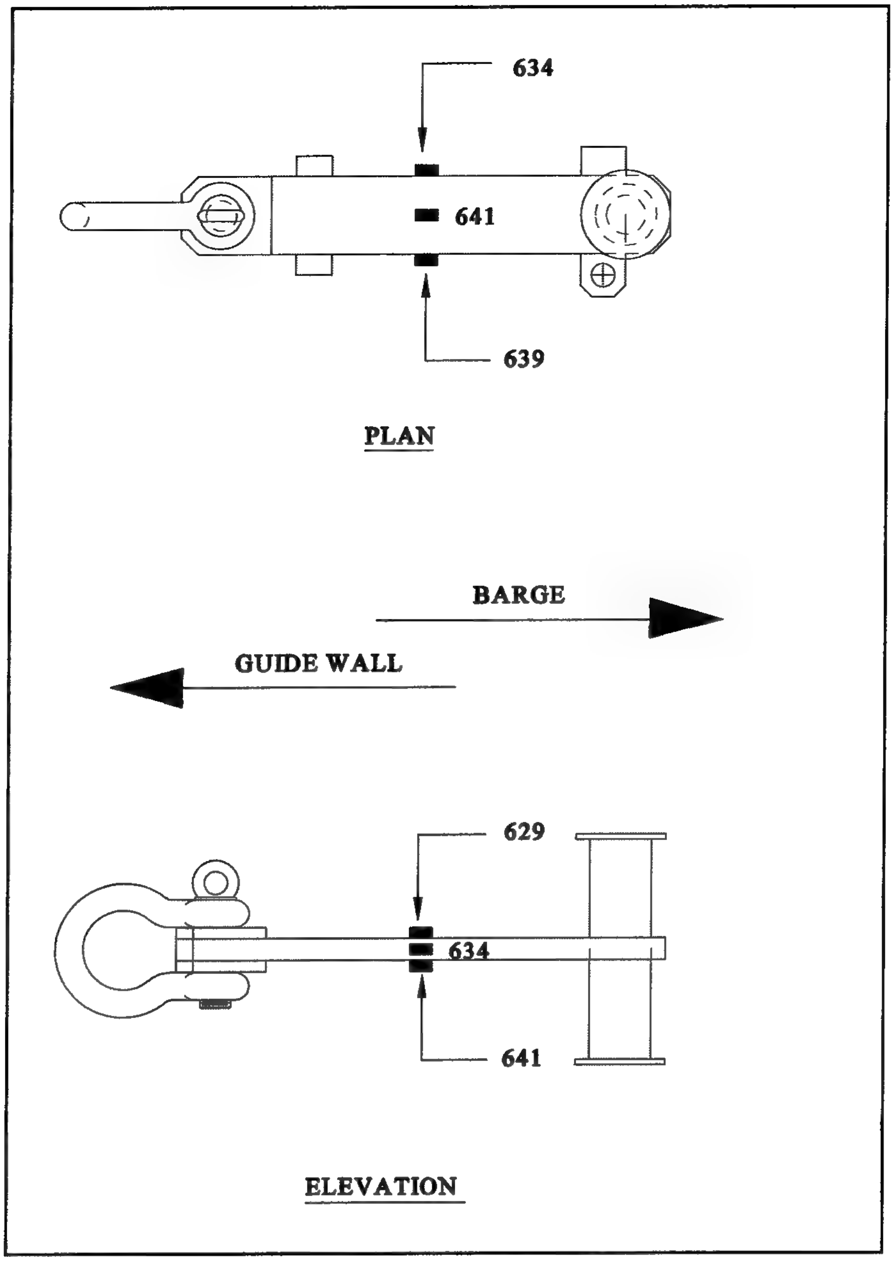


Figure 4. Strain transducer locations, Experiment 1 (slow discharge, third mooring line)

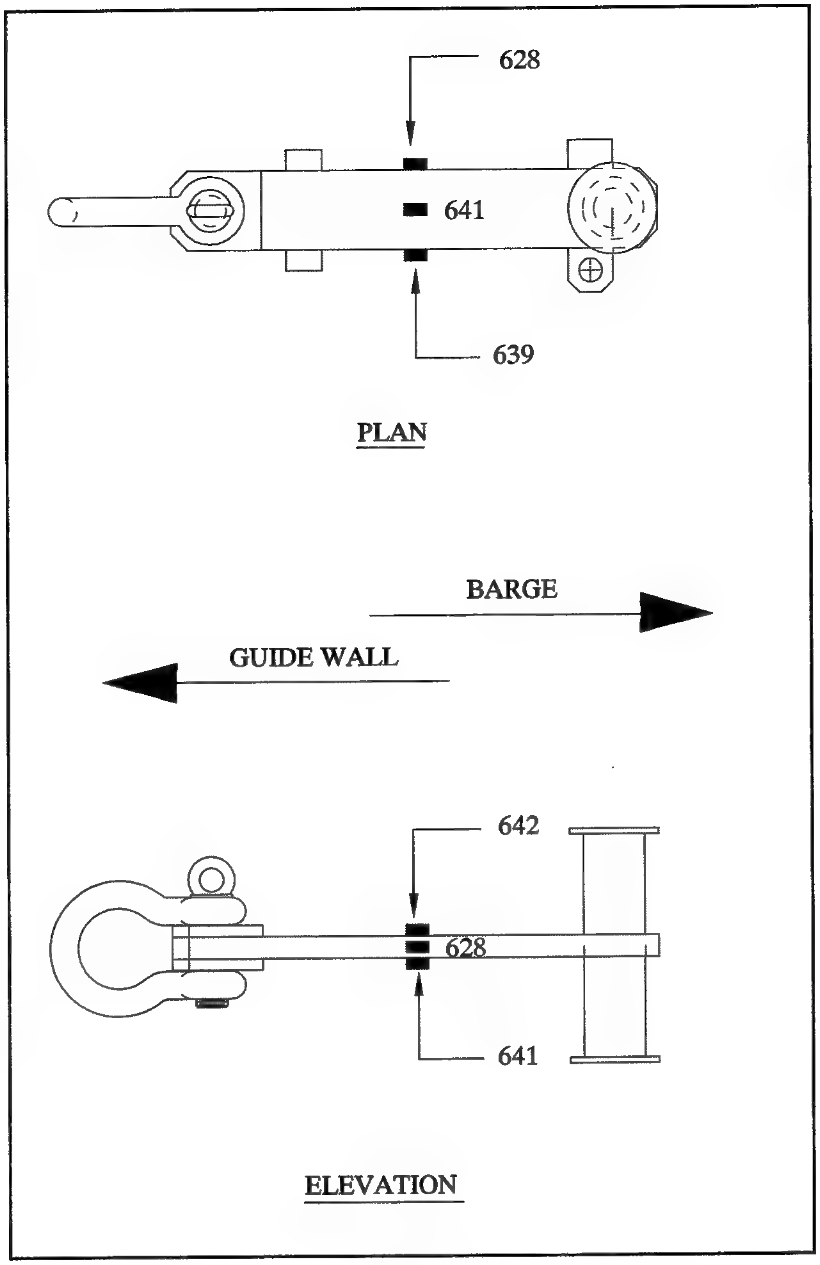


Figure 5. Strain transducer locations, Experiments 2 and 3 (typical discharge)

3 Hydraulic Considerations

General Description

The headwater (HW) elevation[1] during the experiments was 356 and the tailwater (TW) el 302, which was an excellent combination to determine the hawser load information. Normal HW in the Kentucky Lock ranges from el 359 to 354 for HW and from el 302 to 304 for the TW. A camera was placed approximately 50 ft downstream of the lower miter gates to record the changes in the TW elevations on a staff gauge during the emptying cycles. Also, during the experiments, the operator of the lock recorded the emptying valve times, position, and lock chamber water-surface elevations.

Configuration

A tow configuration three barges wide by five long was used. Fourteen of the barges had a draft of 9.5 ft, and one of them was empty with approximately 1.0 ft of draft. The tow was moored in two locations. During the first and second experiment, the barges were located at the third row of line hooks, approximately 200 ft downstream of the miter gates (Figure 6). The third test was performed using the first row of line hooks, approximately 75 ft downstream of the lower miter gates.

Discharge

Figure 7 shows the average discharge computed from observed stages in the lock chamber that are produced at the different intervals of the step-valve operation used during the second emptying cycle. A maximum of approximately 4,500 cfs can be observed 10 min into the cycle. During the first experiment, no discharge measurements were available. In the third experiment, the maximum average discharge computed was in the 8,800-cfs range as shown in Figure 8.

[1] All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

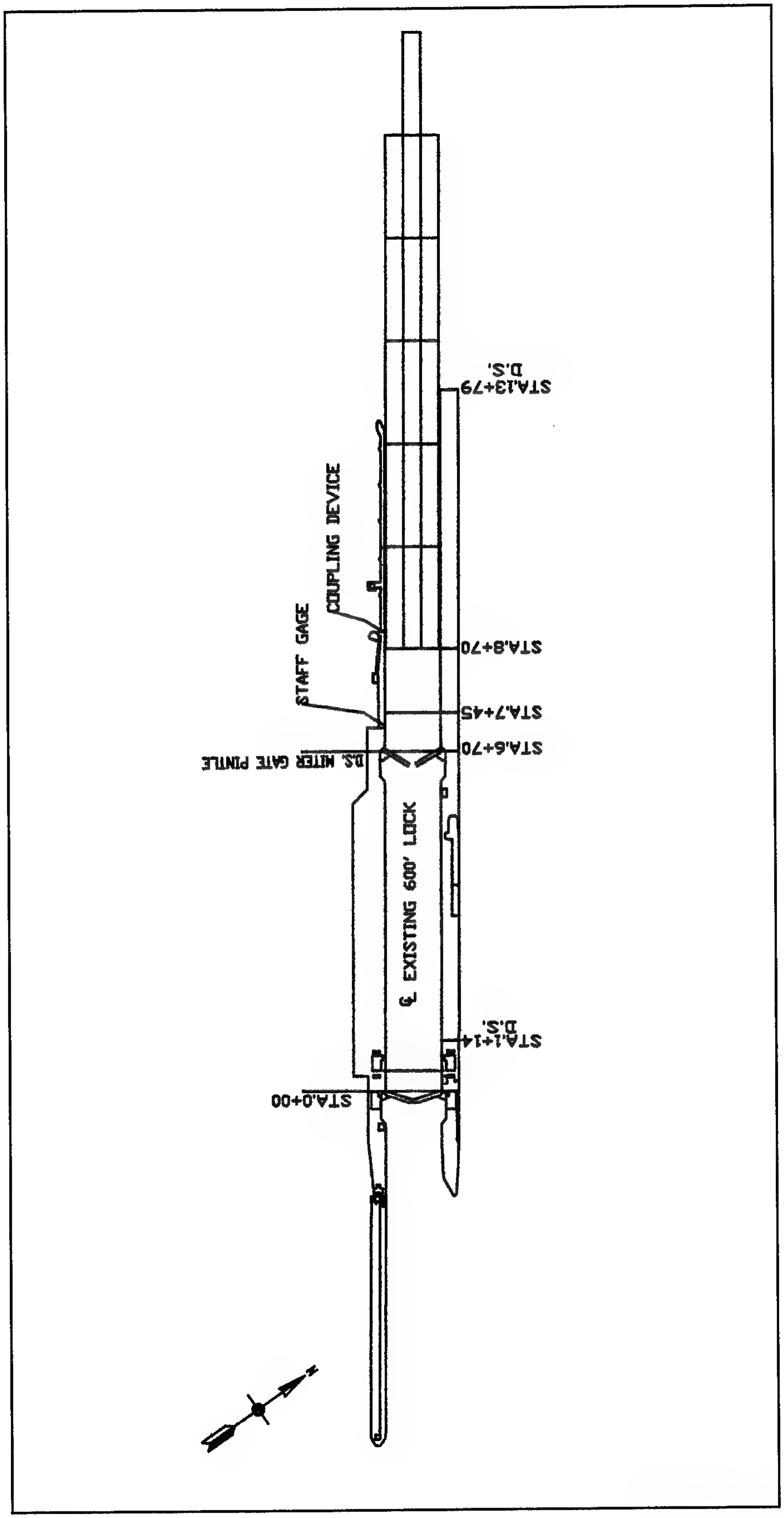


Figure 6. Plan view of Experiment 2 setup

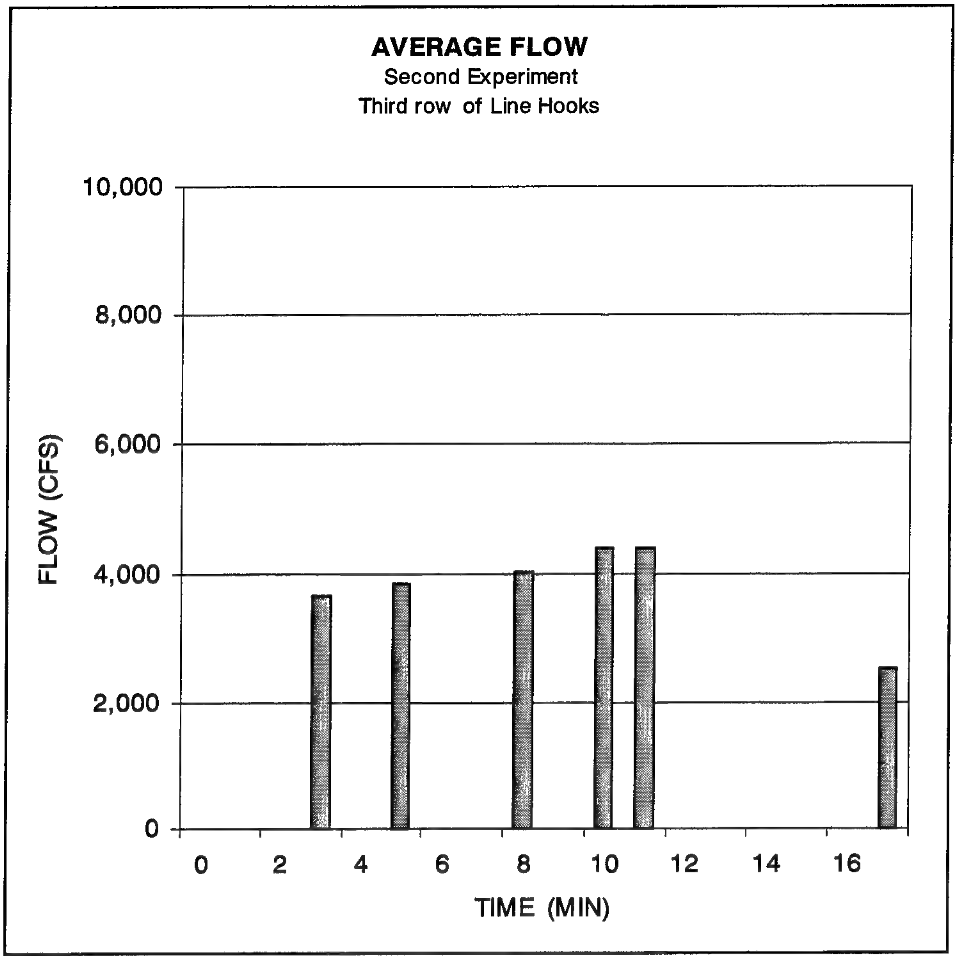


Figure 7. Average flow, Experiment 2

Hawser Forces

A hawser force in these experiments is considered to be the tensile force in the line used to moor the tow and barge arrangement to the lower guide wall. The force in this line is caused by barge movement because of acceleration, drag, and tow thrust forces. One of the purposes of these experiments was to further investigate these forces and gain a better understanding of the dominant forces. The acceleration forces result from differences in water-surface elevations in the lower approach caused by the lock emptying discharge. With the lock discharge outlet in a confined area, the emptying discharges cause the water surface in the vicinity of the outlet to bulk up creating a water-surface slope. This downstream sloping water surface causes the barges and tow to accelerate in the downstream direction. The mooring lines prevent this acceleration, and tensile forces occur in the mooring lines. The force in the line because of the water-surface slope has generally been considered to be a dominant component of the hawser force. Drag forces are caused by the velocities in the lower lock approach from the

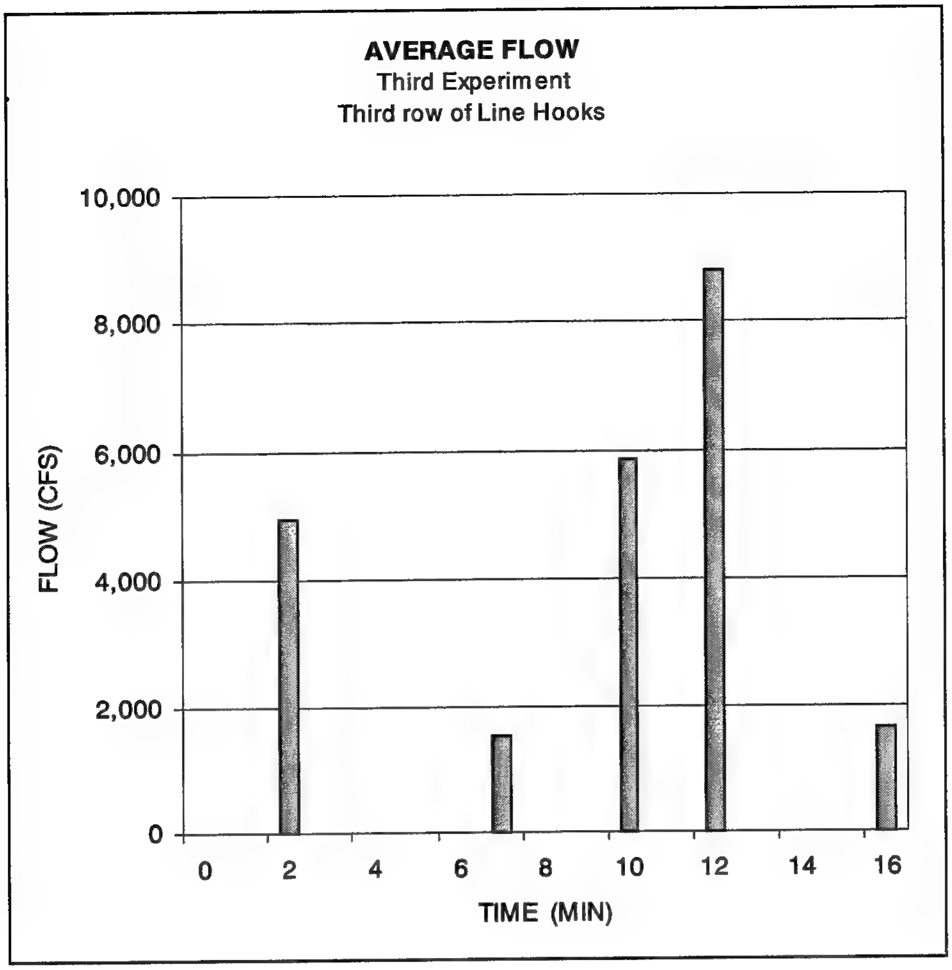


Figure 8. Average flow, Experiment 3

emptying discharge. Tow thrust forces result from the towboat maintaining tension in the mooring lines to prevent dynamic loadings. In the lower lock approach at the existing Kentucky Lock, a towboat generally applies idle speed thrust in a downstream direction (reverse thrust) for normal lock operations.

Figure 18 in Chapter 5 presents the step-valve operation used by the lock operator during the second experiment. By making a comparison between the time when the valve finished each cycle and the time when the peak loads were obtained, the impact of the flow surge on the mooring lines can be noted.

The water surface slope was estimated between the staff gauge, which is located 50 ft downstream of the lower miter gates, and the downstream end of the tow. The slope during the second emptying cycle ranged from +1 to +0.5 ft over a 1,200-ft length of lower approach. The positive sign indicates the upstream part of the tow was being pushed downstream. Each time the valve was opened, the surge on the water surface was observed. One should note that the maximum slope occurred at the beginning of the operation. It is uncertain how much of the loads measured is related to the slope and how much is related

to drag and other external forces acting on the barges. Additional measurements are needed to accurately define the water-surface slope and to determine its effect in the load measurement.

4 Procedures to Calculate Axial Loads

The axial loads were calculated in the following manner. The strain values from Experiment 2 for Transducers 628, 641, and 639 (29.05, 1,176.3, and 148.2 microstrains, respectively) at 68.0 sec are used to determine the stress values. The following equation (Hooke's law) is a standard relationship between stress and strain (Popov 1976)[1]:

$$\sigma^t = \epsilon^t E$$

where

σ^t = stress at time t

ϵ^t = strain obtained during test at time t

E = modulus of elasticity for steel (29,000 ksi)

$$\sigma_{628} = 29.05 \times 10^{-6} \text{ x } 29000 \text{ ksi} = 0.84 \text{ ksi (T)}$$
$$\sigma_{641} = 1176.3 \times 10^{-6} \text{ x } 29000 \text{ ksi} = 34.11 \text{ ksi (T)}$$
$$\sigma_{639} = 148.2 \times 10^{-6} \text{ x } 29000 \text{ ksi} = 4.30 \text{ ksi (T)}$$

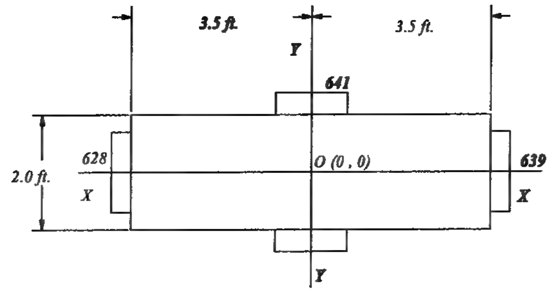
Using the general form of the equation below,

$$A(x)+B(y)+C=\sigma_i$$

where

x and y = coordinates of strain transducers assuming origin at center line of plate as shown below

[1] Popov, E. P. (1976). *Mechanics of materials.* 2d ed., Prentice-Hall.



σ_i = stress at location x, y

A, B = normal vector to plane

C = axial stress

Substituting the values of σ_i and the corresponding coordinates, one has,

$$A(-3.5)+B(0.0)+C = 0.84$$

$$A(0.0)+B(1.0)+C = 34.11$$

$$A(3.5)+B(0)+C = 4.30$$

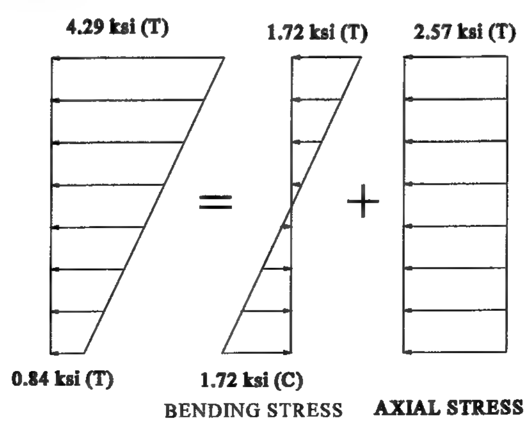
Solving for A, B, and C, one obtains,

$A = 0.494$

$B = 31.54$

$C = 2.57$

With the axial stress value ($C = 2.57$ ksi) and the stresses for Transducers 628 and 639, the stress diagram can be drawn and is presented below.



To determine the axial load, the axial stress is multiplied by the sectional area (14.0 in^2.).

$Pa = 2.57 \times 14.0 = 35.98$ kips

5 Tests Results

Experiment 1, Slow Discharge Rate, Third Mooring Line

Figures 9 and 10 show the strain time-history for Transducers 641, 639, and 634. One can observe that the maximum strain of 800 microstrains occurs at about 1,100 sec. Strain readings were translated to stresses shown in Figures 11 and 12. Maximum stresses of 23.0 and 25.0 ksi occurred at 300 and 1,150 sec, respectively, after discharge started. Figure 13 shows the axial load time-history. In this figure, one can observe that the maximum axial load is about 30.0 kips.

Experiment 2, Typical Discharge Rate, Third Mooring Line

Strain time-histories for Transducers 641, 642, 628, and 639 are shown in Figures 14 and 15. At about 68 sec, strains of about 1,200 and 150 microstrains, respectively, were observed. After this maximum value, an additional series of maximum points of 900-1,000 and 100 to 120 microstrains are seen with strains for Transducers 641-642 and 628-639, respectively. These maximum points represent the different valve openings. Figures 16 and 17 show the stress time-histories, where the maximum stresses occurred at about 68 sec after the discharge started and had a magnitude of about 35.0 ksi, which is below the yield strength (36.0 ksi) of the steel device, indicating that yield did not occur. The maximum stresses after each valve increment at 200, 350, 450, and 575 sec were 23.0, 25.0, 28.0, and 28.0 ksi, respectively. Stresses were translated to the bending and axial components using the procedures indicated in Chapter 4, where the axial component was used to calculate the axial load time-history shown in Figure 18. The maximum axial tensile load was about 37.0 kips. For this experiment, readings obtained from Transducer 642 were not used because readings shown in Figures 14 and 16 indicate that the transducer was not working appropriately.

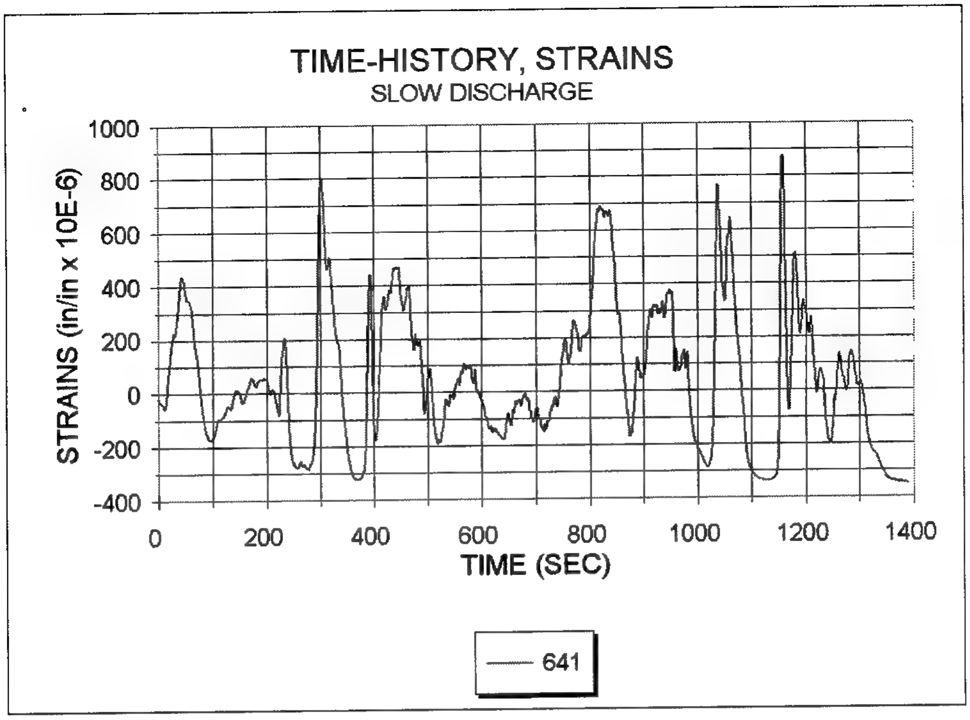


Figure 9. Strain time-history, Experiment 1 (Transducer 641)

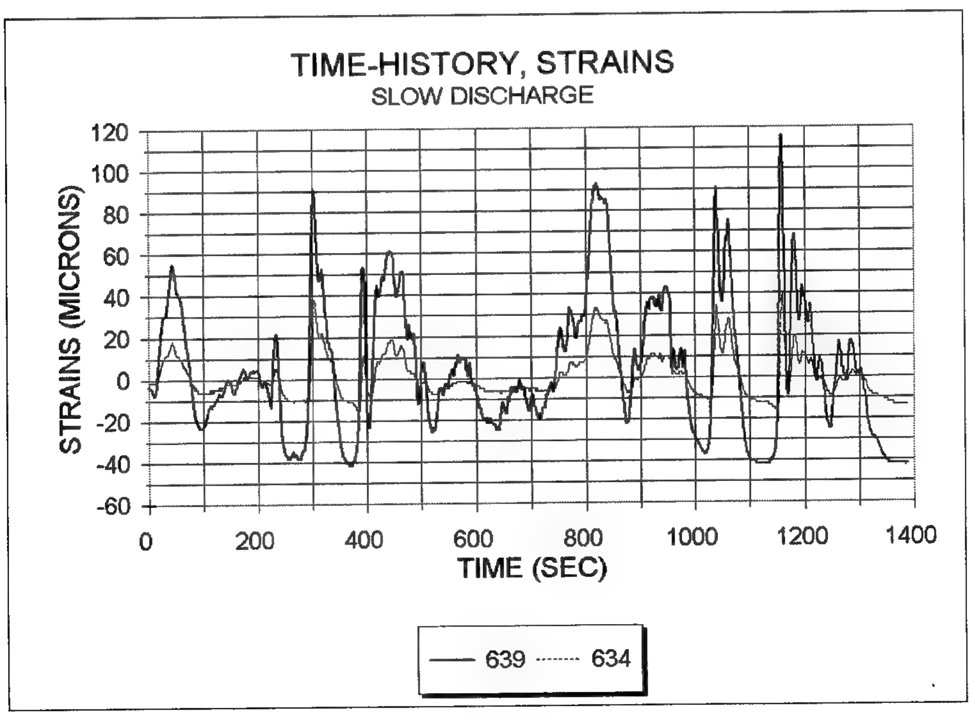


Figure 10. Strain time-history, Experiment 1 (Transducers 639 and 634)

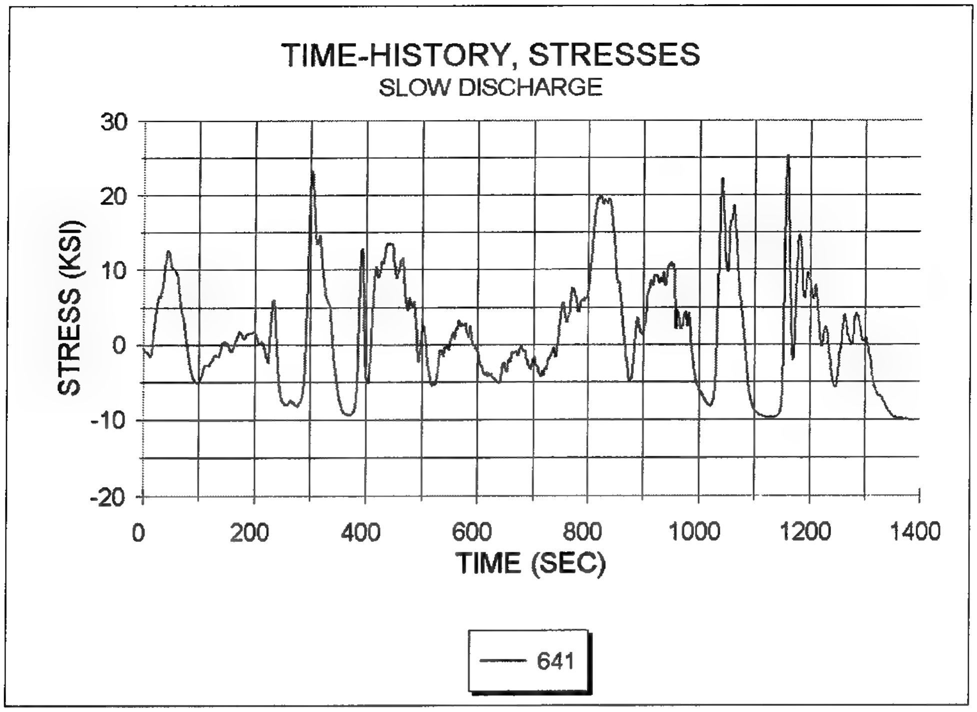


Figure 11. Stress time-history, Experiment 1 (Transducer 641)

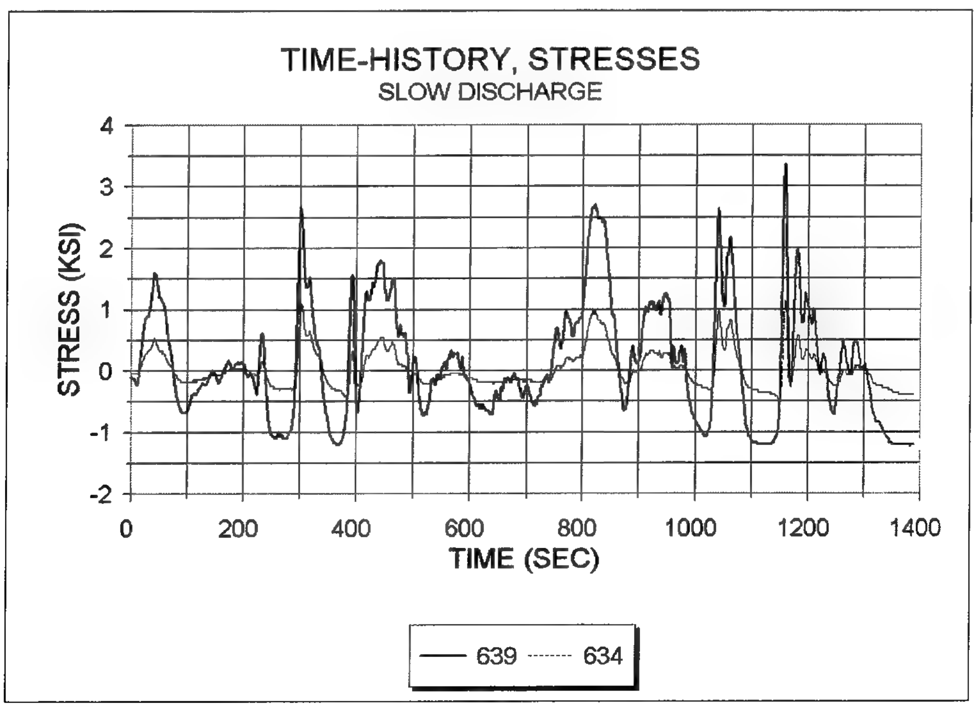


Figure 12. Stress time-history, Experiment 1 (Transducers 639 and 634)

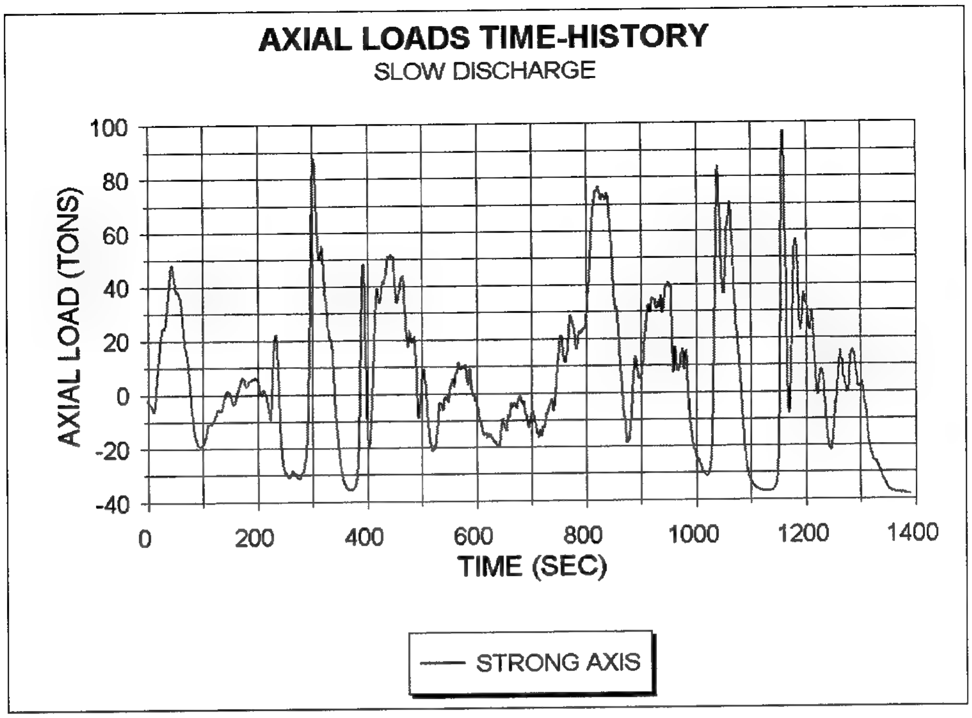


Figure 13. Axial load time-history, Experiment 1

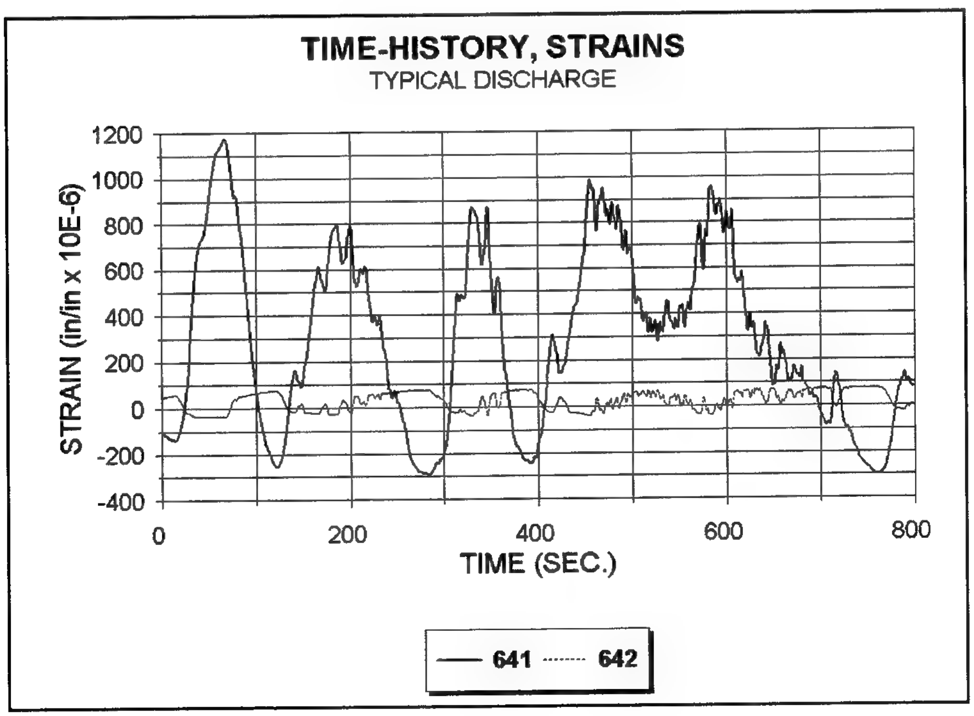


Figure 14. Strain time-history, Experiment 2 (Transducers 641 and 642)

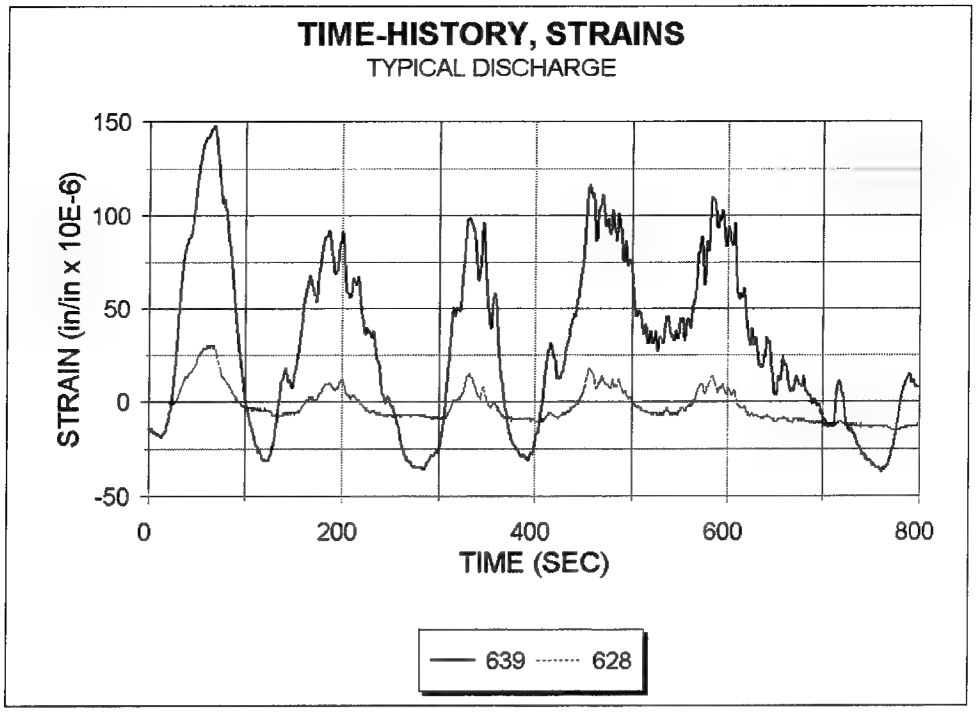


Figure 15. Strain time-history, Experiment 2 (Transducers 628 and 639)

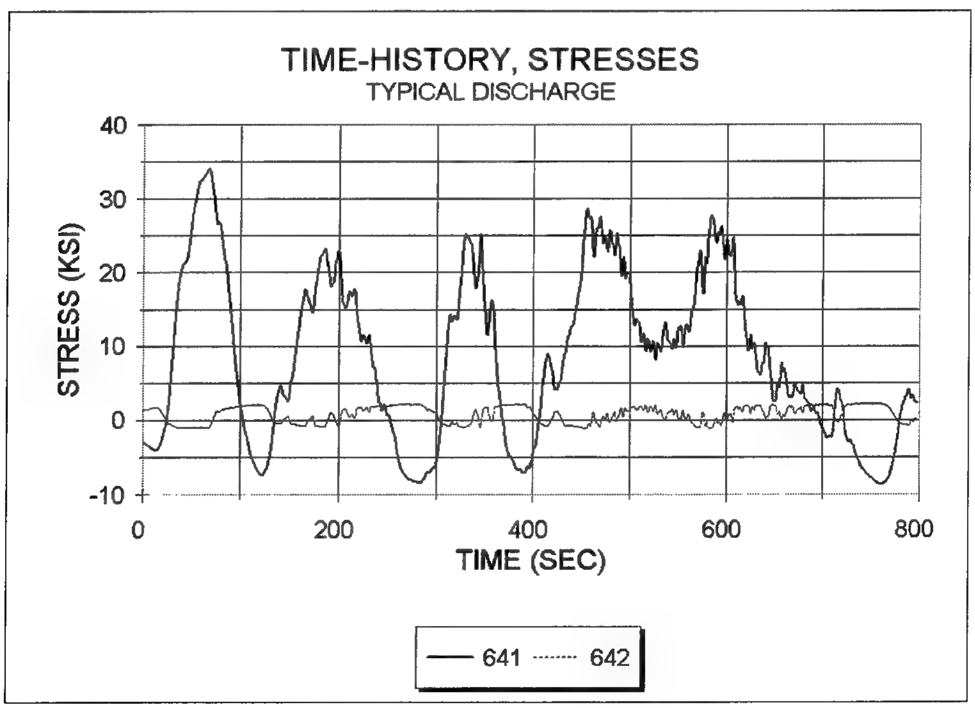


Figure 16. Stress time-history, Experiment 2 (Transducers 641 and 642)

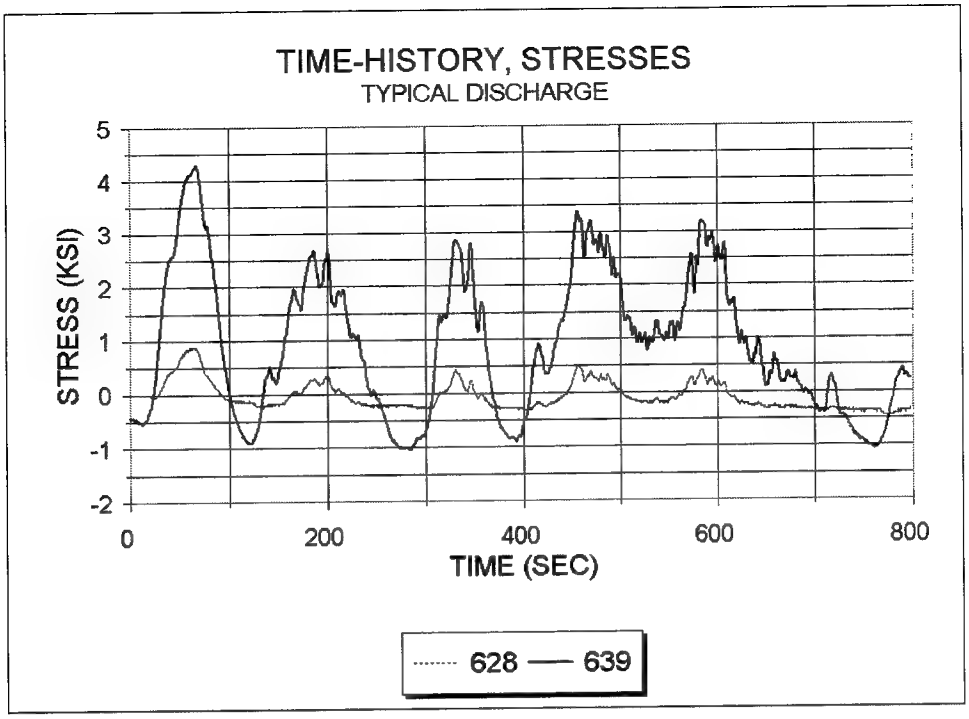


Figure 17. Stress time-history, Experiment 2 (Transducers 628 and 639)

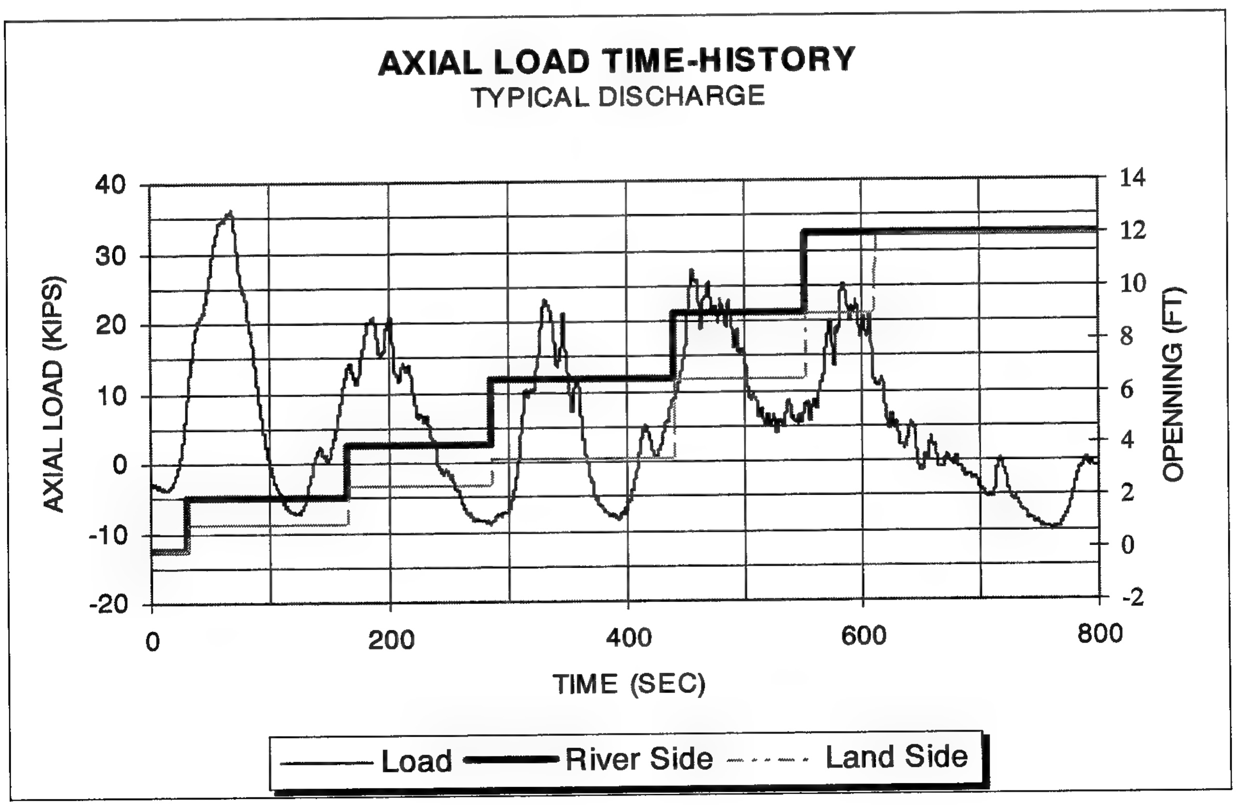


Figure 18. Axial load time-history and valve operation, Experiment 2

Experiment 3, Typical Discharge Rate, First Mooring Line

Strain time-histories for Transducers 641, 642, 628, and 639 are shown in Figures 19 and 20. Maximum strains of about 1,050.0 and 150.0 microstrains occurred at about 60 sec for Transducers 641-642 and 628-639, respectively. A series of maximum points can also be observed with strains in the range of 950-1,000 and 140 to 150 microstrains for Transducers 641-642 and 628-639, respectively. Similar to Experiment 2, these observed points represent the different valve openings. Figures 21and 22 show the stress time-histories, where the maximum stresses occurred at about 60 sec after the discharge started and had a magnitude of about 31.0 ksi. The maximum stresses for Transducers 641 and 642 after each valve increment at 250, 425, and 600 sec were 28.0, 29.0, and 27.0 ksi, respectively. As explained in Experiment 2 results, the stresses were translated to the bending and axial components, and the axial component was used to calculate the axial load time-history shown in Figure 23. The maximum axial tensile load was about 40.0 kips. As in Experiment 2, the readings for Transducer 642 were not used because readings shown in Figures 19 and 21 indicate that the transducer was not working appropriately.

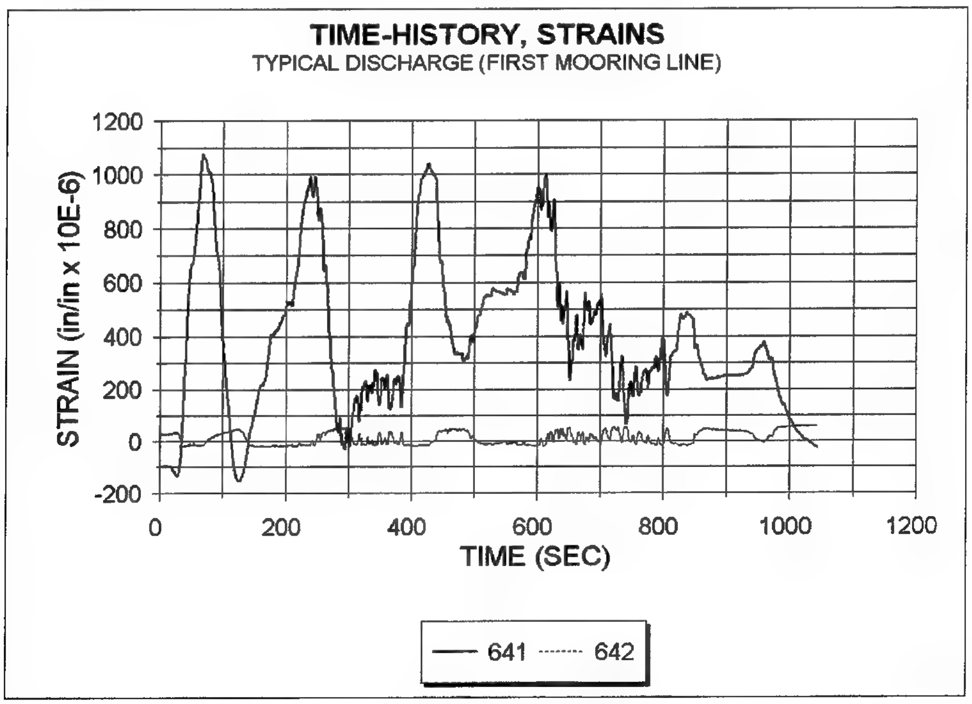


Figure 19. Strain time-history, Experiment 3 (Transducers 641 and 642)

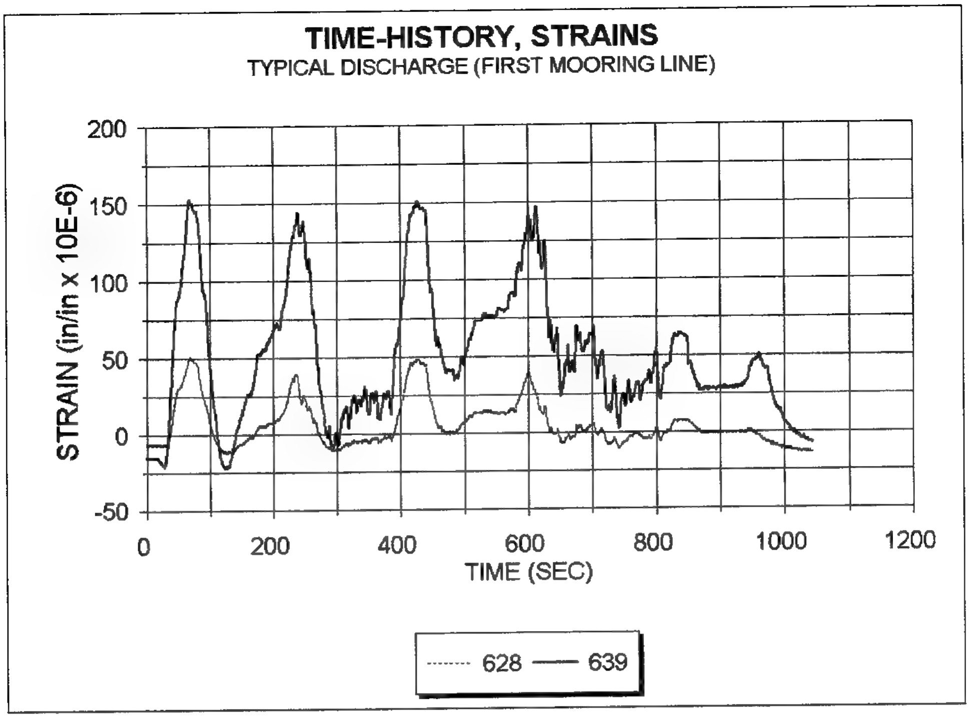


Figure 20. Strain time-history, Experiment 3 (Transducers 628 and 639)

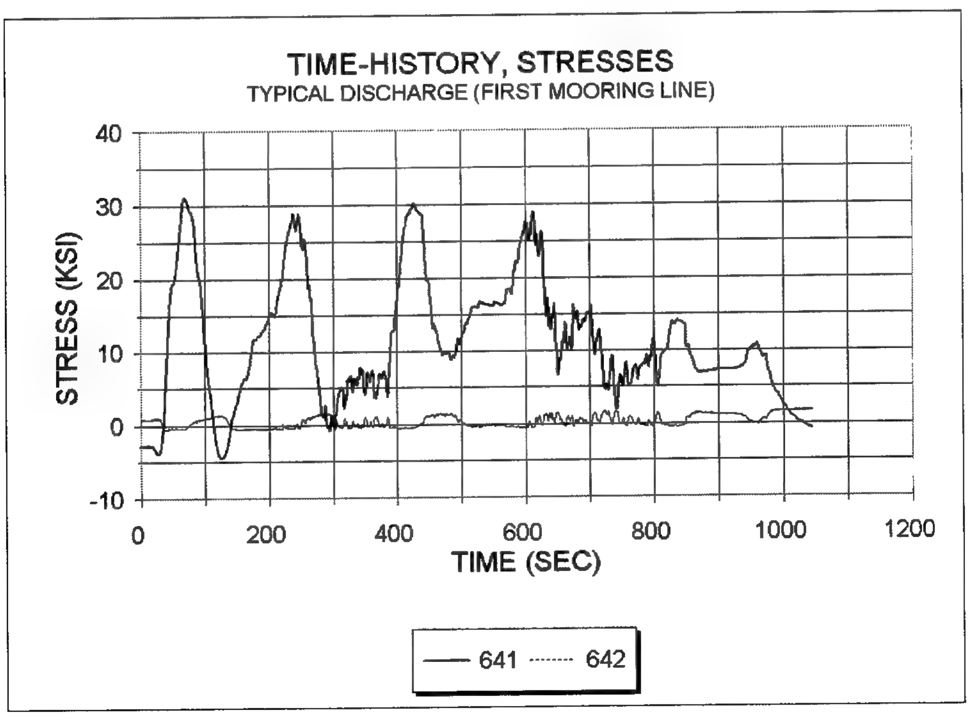


Figure 21. Stress time-history, Experiment 3 (Transducers 641 and 642)

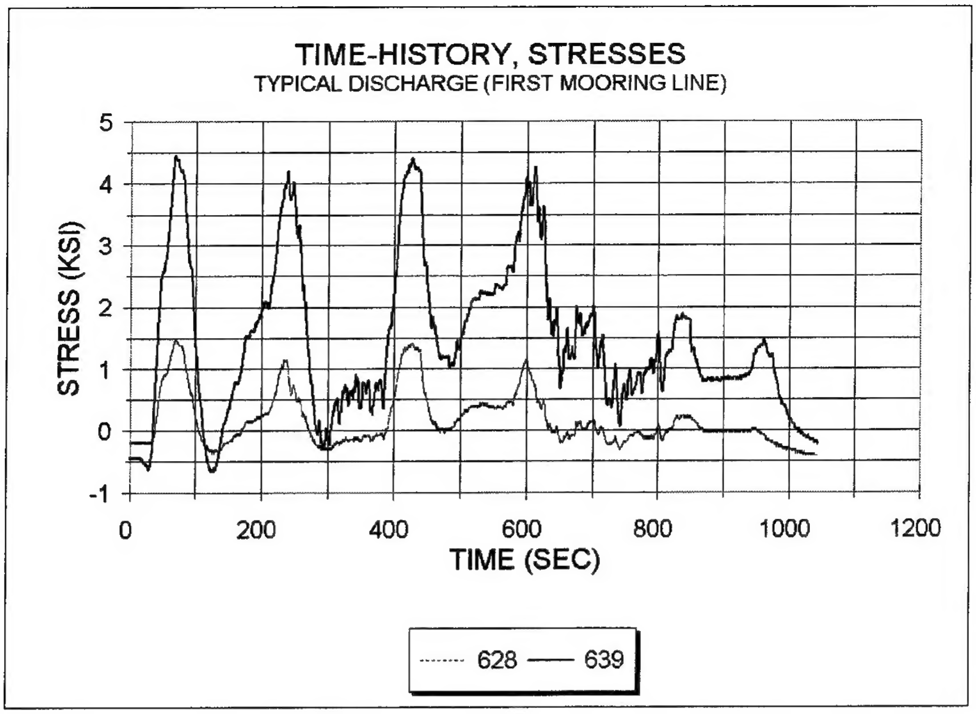


Figure 22. Stress time-history, Experiment 3 (Transducers 628 and 639)

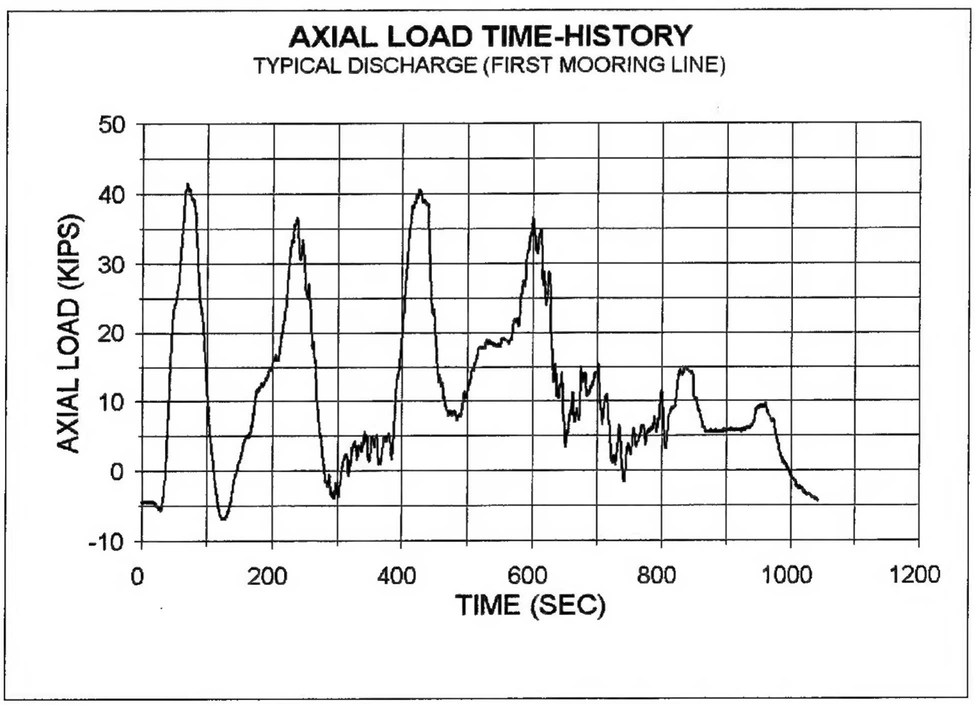


Figure 23. Axial load time-history, Experiment 3

6 Conclusions and Recommendations

The results of the hawser load test conducted on the Kentucky Lock show that loads applied to the downstream guide wall for these experiments are in the range of 30.0-45.0 kips. This experimental work constitutes the first known tests of this kind.

The data from these experiments approximate the loads that are being experienced in the downstream guide wall of the Kentucky Lock and can aid in the selection of a discharge system for the proposed lock. Currently, two discharge systems are being considered for the proposed lock. One lock discharge plan uses an interlaced lateral system located downstream of the lower miter gate pintle. The other alternative is a landside channel that discharges downstream of the lower approach guide wall. Hawser load information for tows moored in the lower approach has been obtained from numerical and laboratory model investigations. Based on the prototype and the model results, the lower cost discharge system (interlaced lateral) could be selected.

The operation of the emptying valves played an important role. As discussed earlier, the time in which the peak loads were obtained coincide with the step-valve operation.

It is recommended that an additional set of tests be conducted using the Structural Testing System with a modified version of the coupling device to reduce the bending and twisting stresses. Bending stresses can be reduced substituting the pipe sections for a shackle similar to the one used in the guide wall side of the device. Also, a similar device with a square cross section can be used to reduce bending stresses.

Additional experiments can be conducted also using a device apparatus that will not have any bending component. One system that can be used is the standard load sensing shackle tension links. This measurement device system consists of a strain gauge circuit installed in a small hole along its longitudinal axis. This arrangement provides an effective means of protection and sealing of the strain gauge while minimizing the effects of the torsional and flexural loads.

Another measurement device that can be used is the clevis pin, which also eliminates the effect of the torsional and flexural loads.

Additional experiments are needed to determine the contribution of water-surface slope, drag, and tow thrust to the overall hawser force in a mooring line. An experimental laboratory investigation would be beneficial in evaluating these different forces. Evaluating forces and flow conditions in a laboratory environment is much easier and less expensive. Once effective methods to evaluate these forces are established in the laboratory, additional prototype experiments should be conducted to substantiate laboratory results. These results would be very beneficial in helping to finalize recommendations for the proposed Kentucky Lock.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Hawser load information for tows moored to the downstream guide wall was requested by the U.S. Army Engineer District, Nashville, to aid in the design of the discharge outlet and guard wall for the 1,200-ft-long lock addition proposed at the Kentucky Lock & Dam. The existing Kentucky Lock is located on the Tennessee River approximately 20 miles southeast of Paducah, KY. Experiments were performed to determine the hawser loads experienced by tows moored to the lower guide wall of the existing 600-ft-long navigation lock and to develop an allowable hawser load. The results of the hawser load experiments conducted on the lock show that loads applied to the downstream guide wall for these experiments are in the range of 30.0-45.0 kips. This experimental work consitutes the first known tests of this kind.

14. SUBJECT TERMS

Hawser load experiments	Navigation
Kentucky Lock and Dam	Prototype evaluation
Locks (waterways)	Tennessee River

15. NUMBER OF PAGES
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